Constraints on Dynamical Dark Energy from the abundance of galaxies at high redshifts

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Collaborators

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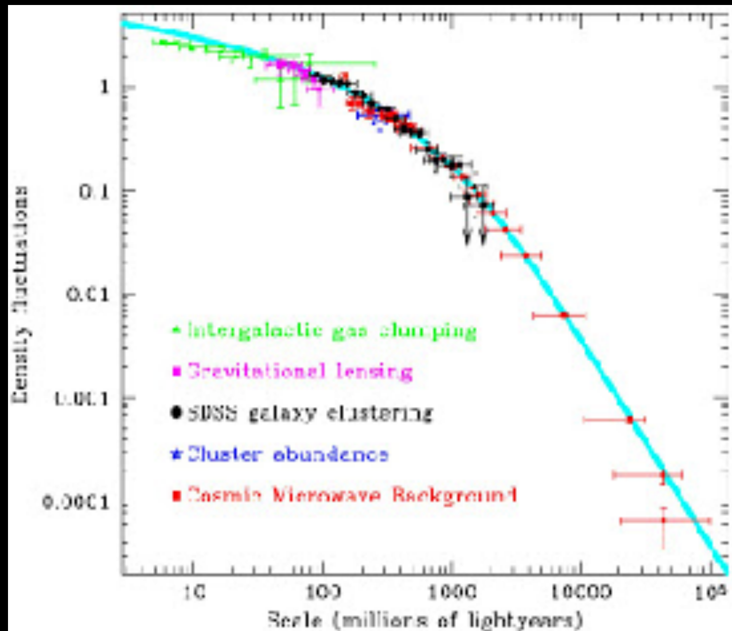
The mass function of DM halos

$10^9\,M_\odot$ $10^{15}\,M_\odot$

$\sigma(M)$



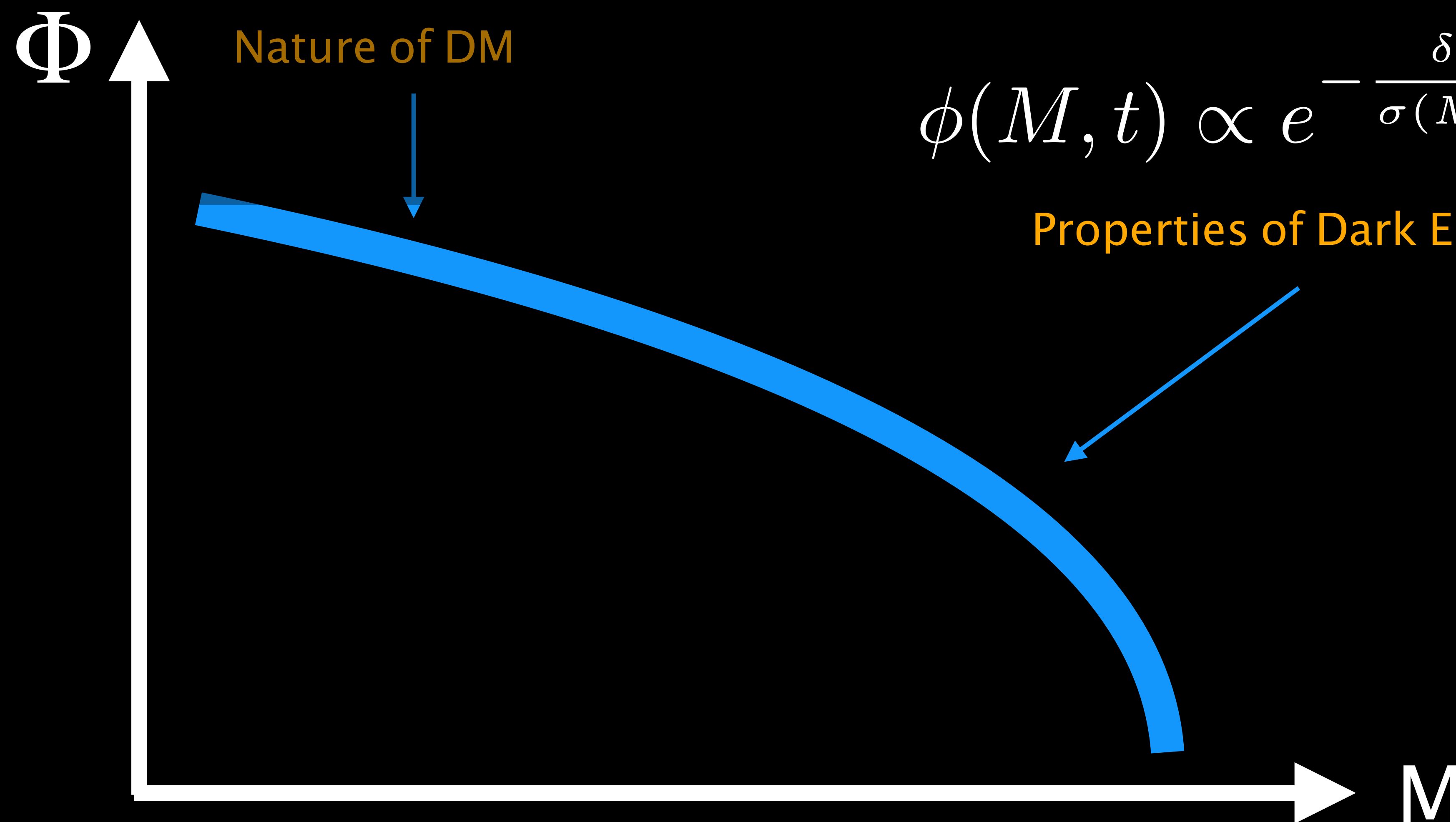
$$\phi \propto \frac{M^{-2}}{\sigma(M)}$$

Nature of DM

Growth factor
of density perturbations

$$\phi(M,t) \propto e^{-\frac{\delta_c^2}{\sigma(M)^2}\frac{1}{D(t)^2}}$$

Properties of Dark Energy



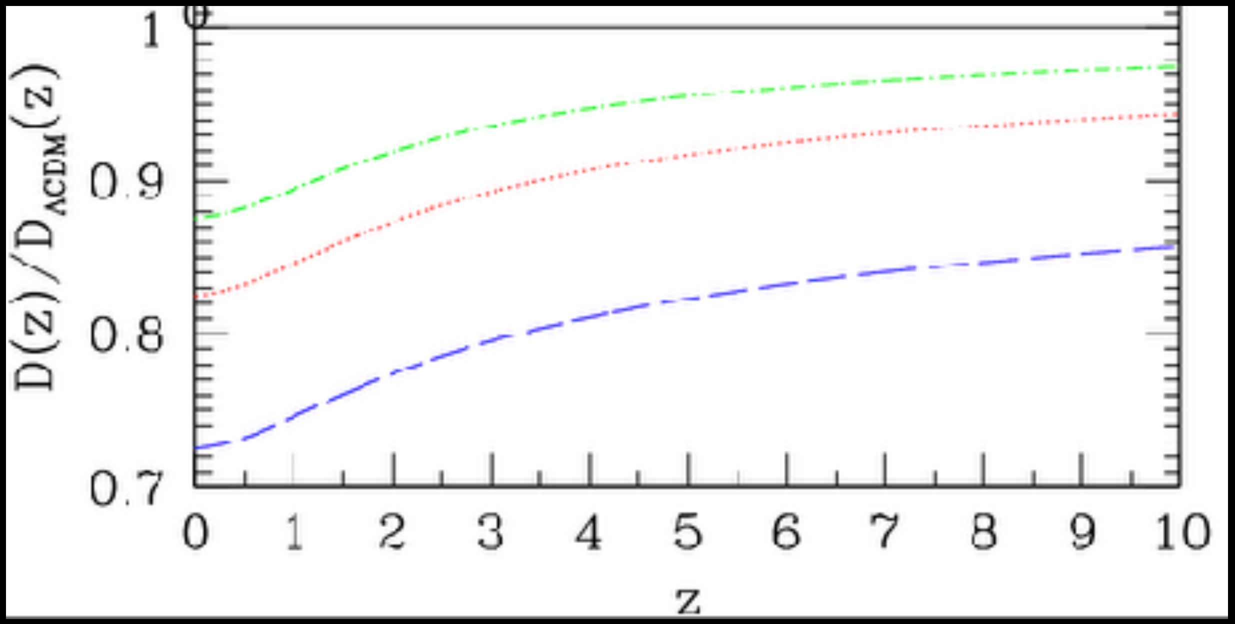
Parametrise evolution of the DE Equation-of-state parameter

$$w(a) = w_0 + w_a\,(1-a)$$

The predicted abundance of massiva halos at a given redshift strongly depends on the growth factor at the corresponding cosmic time

$$\phi(M,t) \propto e^{-\frac{\delta_c^2}{\sigma(M)^2}\frac{1}{D(t)^2}}$$

$$H^2 = H_0^2\left[\Omega_M a^{-3}\,\Omega_\Lambda\,a^{-3(1+w_0+w_a)}\,e^{3w_a(a-1)}\right]$$



$$\delta(a) = a\,exp\left(\int_0^a [\Omega(a)^\gamma - 1]\,d\,lna\right)$$

$$\Omega(a) = \Omega_0 a^{-3}/(H(a)/H_0)^2$$

Linder 2005

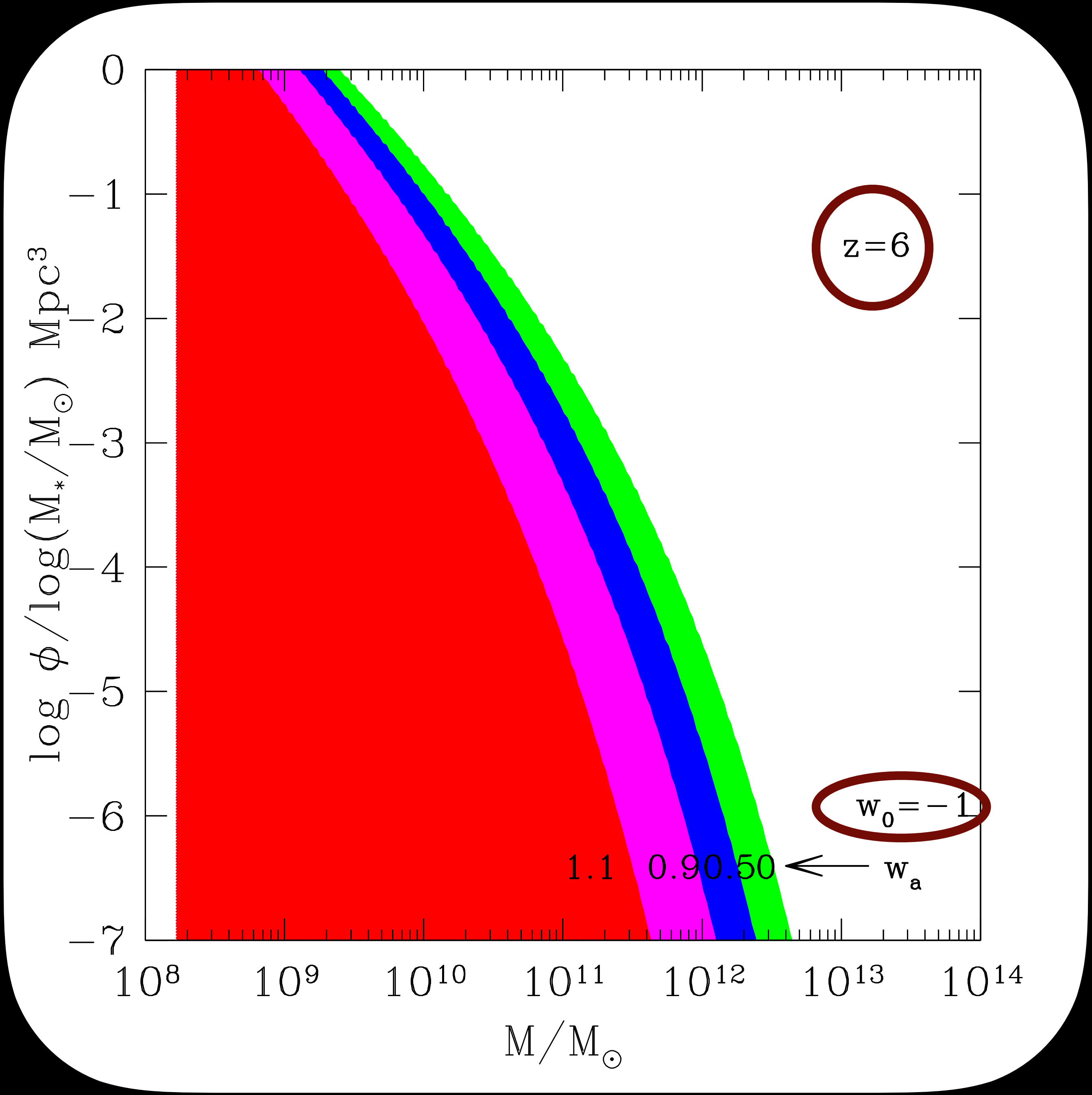
$$\gamma = 0.55 + 0.05(1+w(z=1))w(z=1) \geq 1$$
$$\gamma = 0.55 + 0.02(1+w(z=1))w(z=1) < 1\,.$$

$$D(t) \propto \delta(t)$$

Normalized to the observed CMB fluctuations

The mass function of DM halos for different (w_0, w_a)

The mass function of DM halos constitutes and upper limit for the abundance of galaxies (galaxies cannot outnumber their DM halos)



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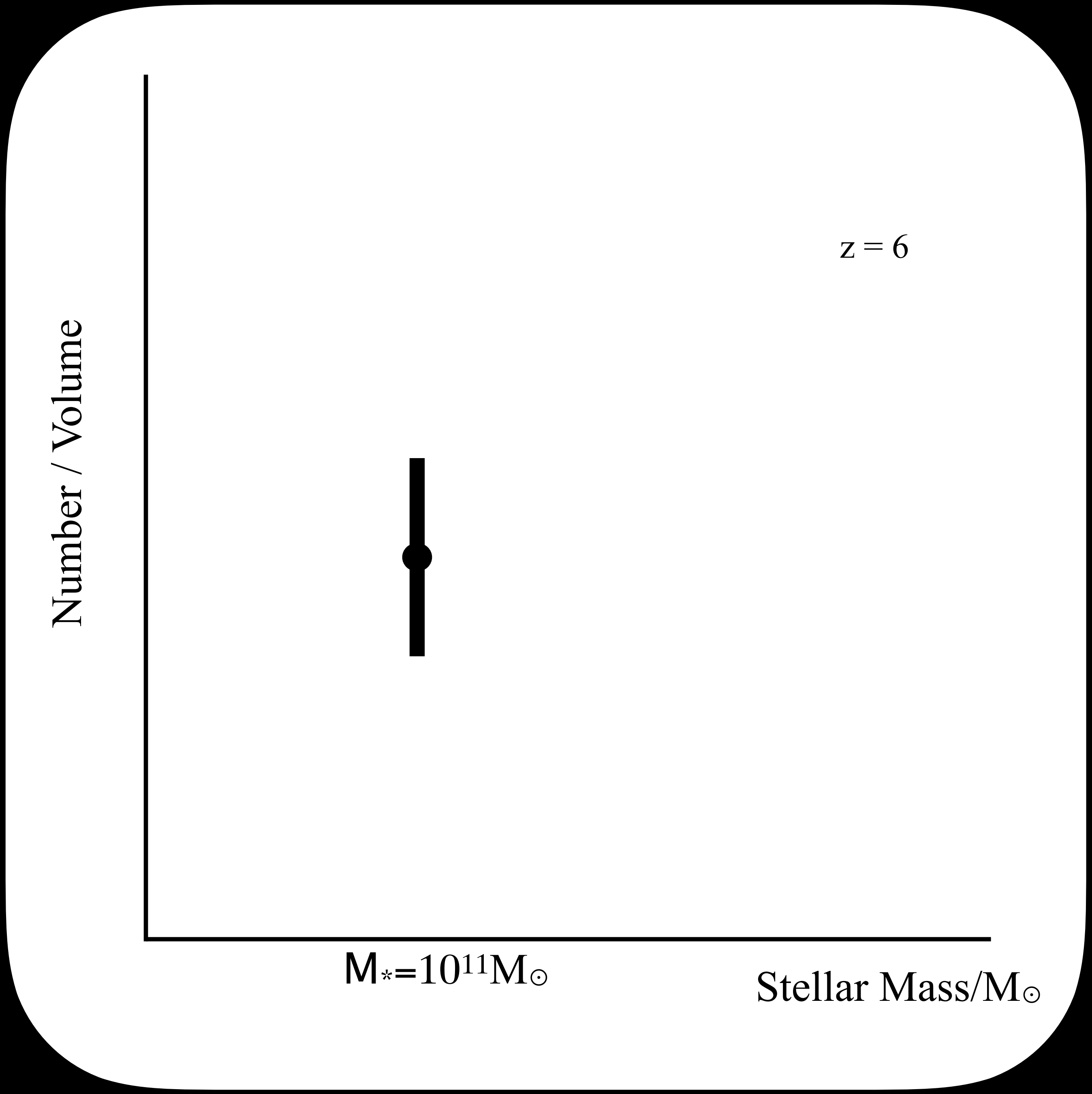
Linder 2005

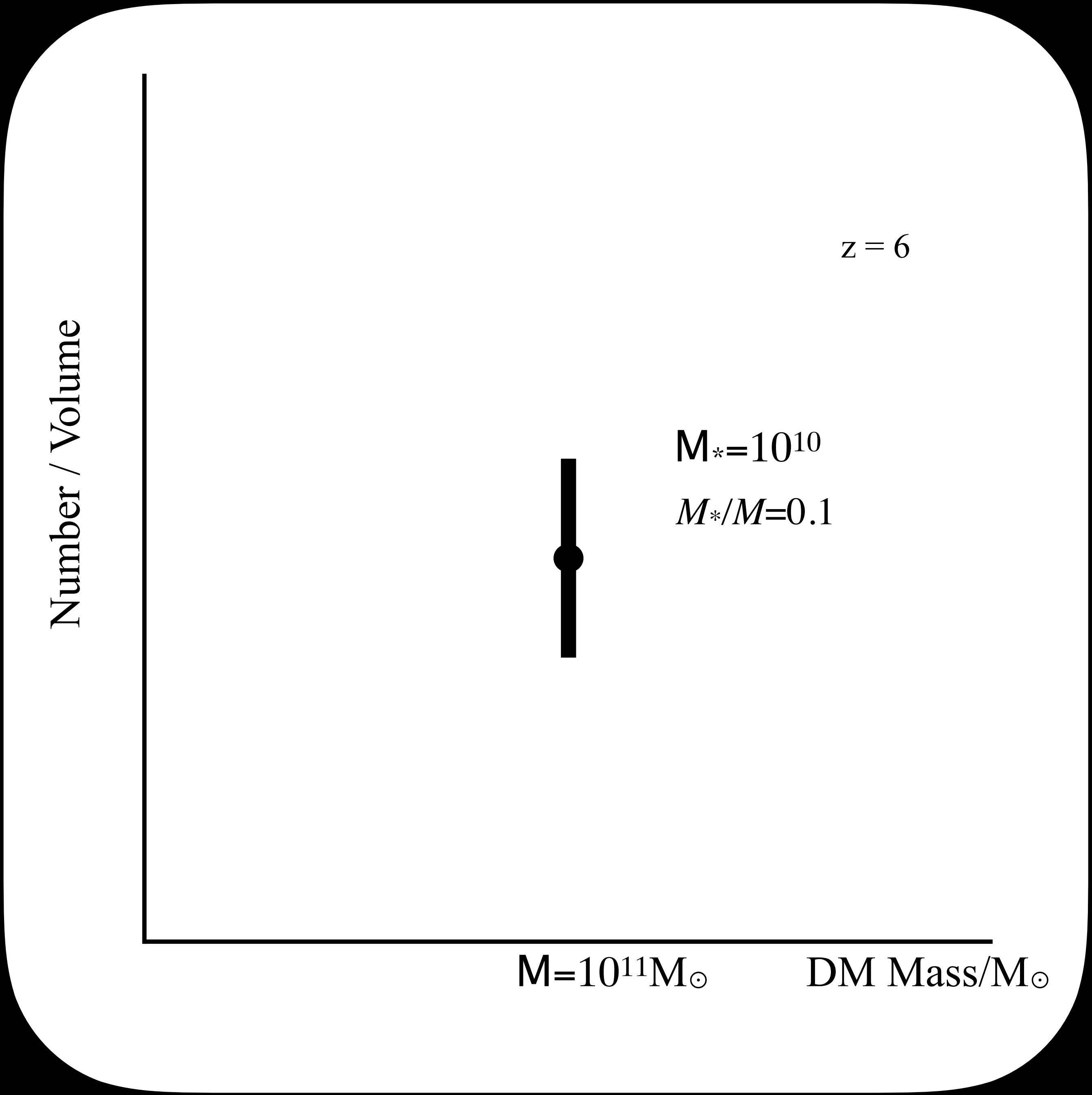
The mass function of DM halos for different (w_0,w_a)

We measure the number density of massive galaxies with given M* at a given redshift



The mass function of DM halos for different (w_0,w_a)

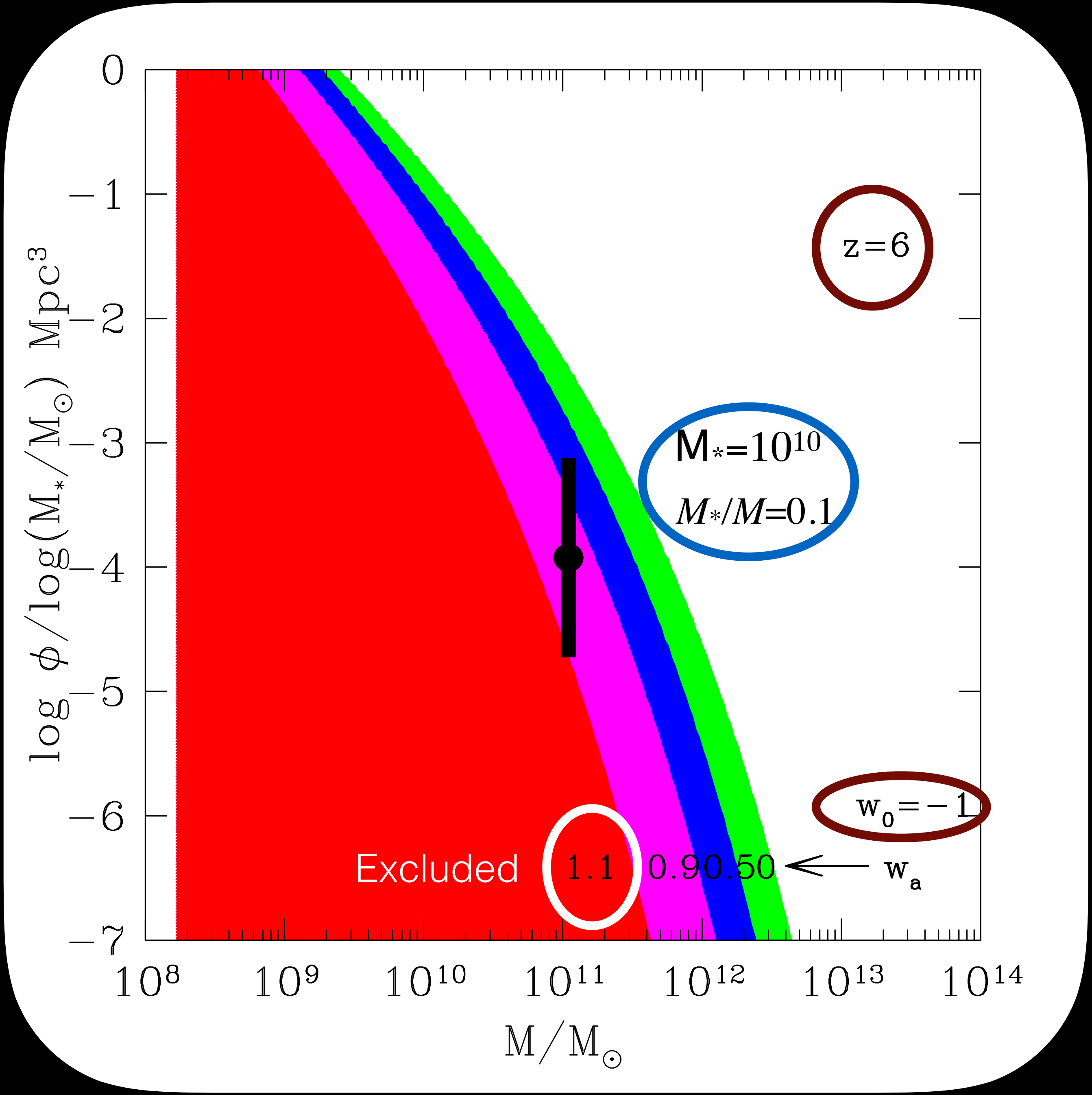
We compute the associated DM mass M assuming an M*/M ratio



The mass function of DM halos for different (w_0,w_a)

Assuming a M*/M ratio, tha observed abundance of galaxies with given stellar mass M* can be translated into an observational lower limit for the halo mass function.

Models predicting mass functions below such lower limit are excluded



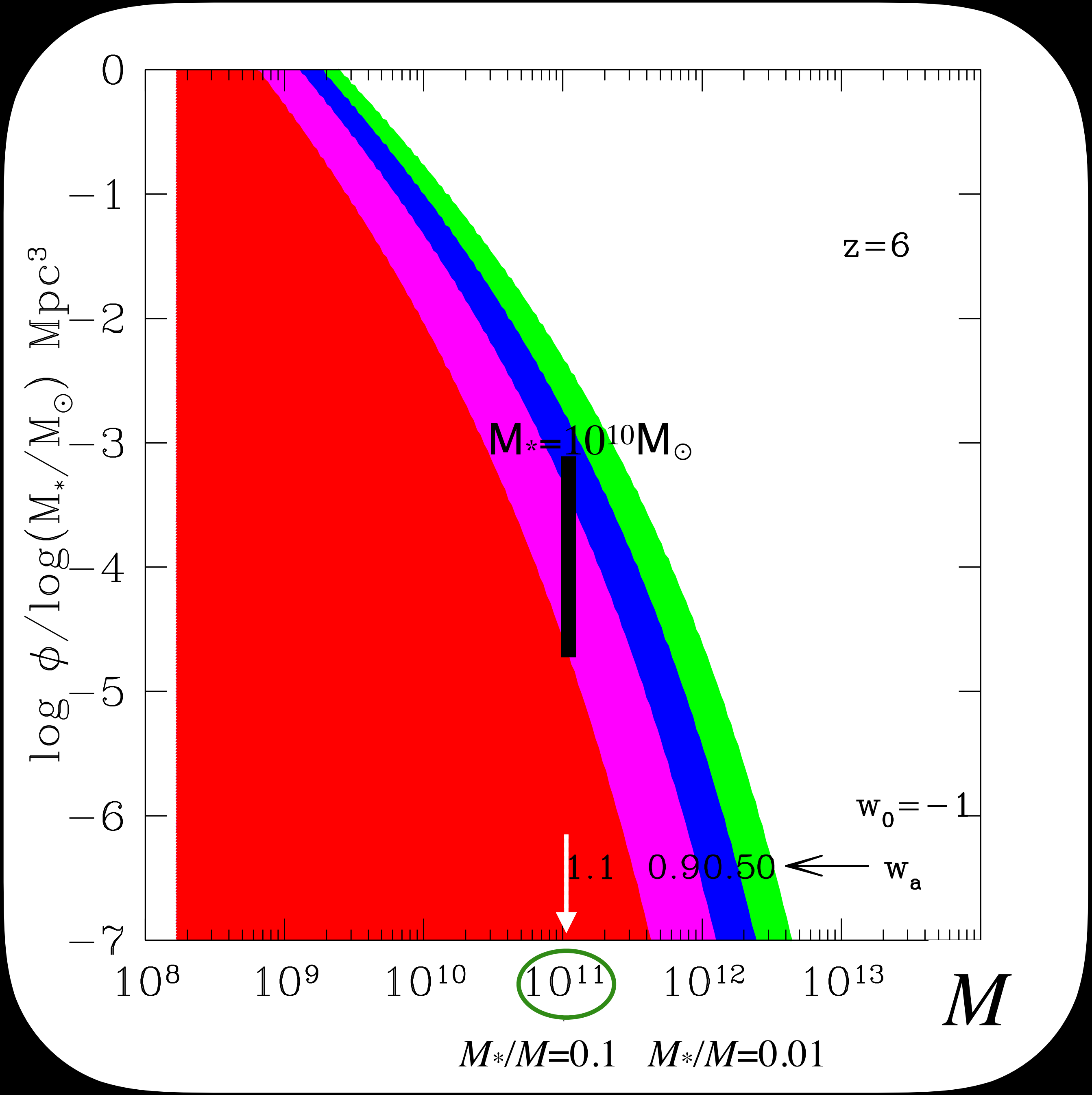
The predicted abundance of massiva halos at a given redshift strongly depends on the growth factor at the corresponding cosmic time

$$\phi(M,t) \propto e^{-\frac{\delta_c^2}{\sigma(M)^2}\frac{1}{D(t)^2}}$$

Observed galaxies cannot Outnumber their host DM halos

The constraint provided by the measured abundance of massive galaxies depend on the M*/M ratio

The smaller M*/M the tighter the constraints



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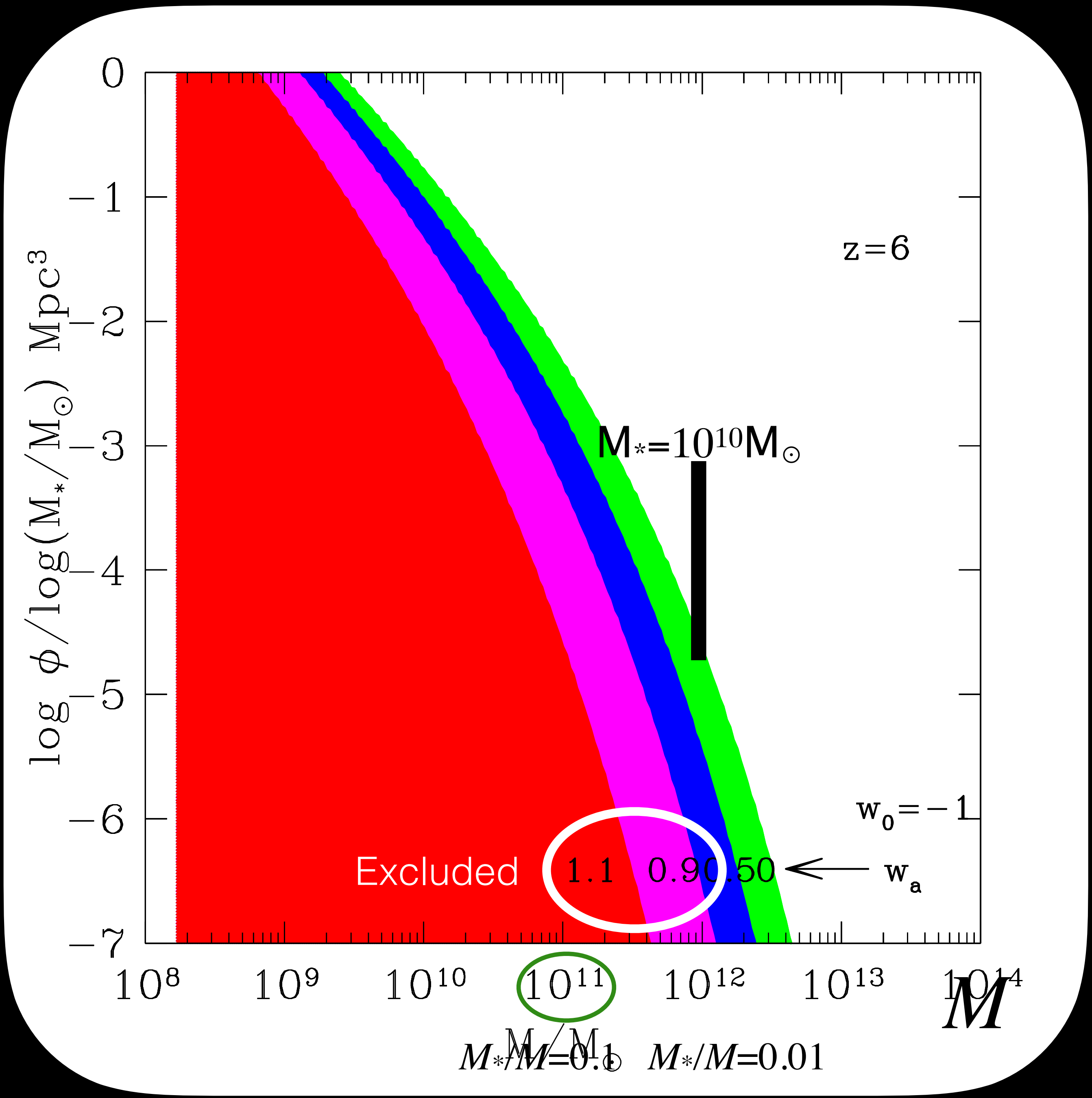

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Linder 2005

I. The Stellar Mass Function of optical/UV galaxies at z=6

$$w(a) = w_0 + w_a\,(1-a)$$

$w_a > 0$ corresponds to positive evolution of w with redshift

$$H^2 = H_0^2 \left[\Omega_M a^{-3}\, \Omega_\Lambda\, a^{-3(1+w_0+w_a)}\, e^{3w_a(a-1)}\right]$$

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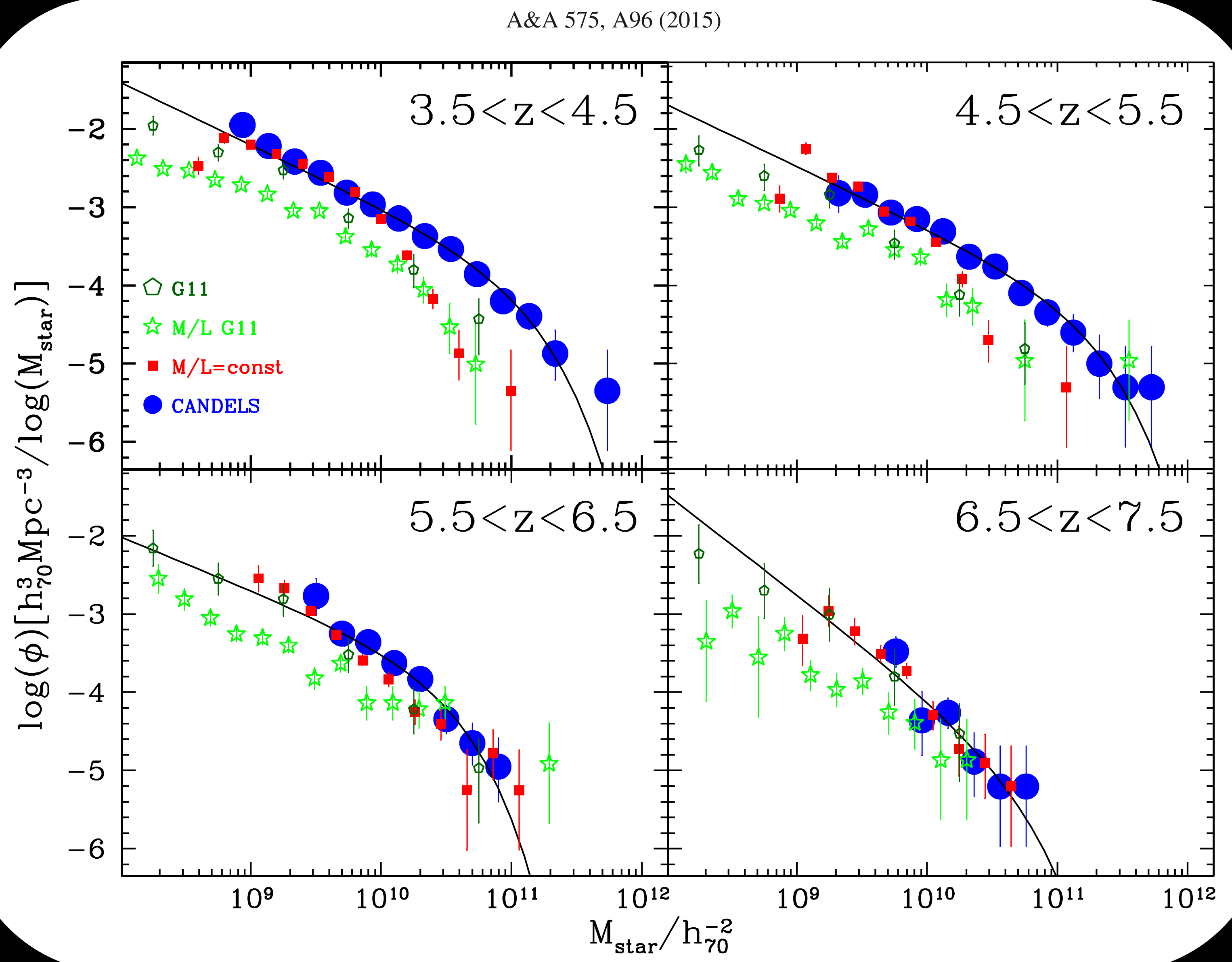


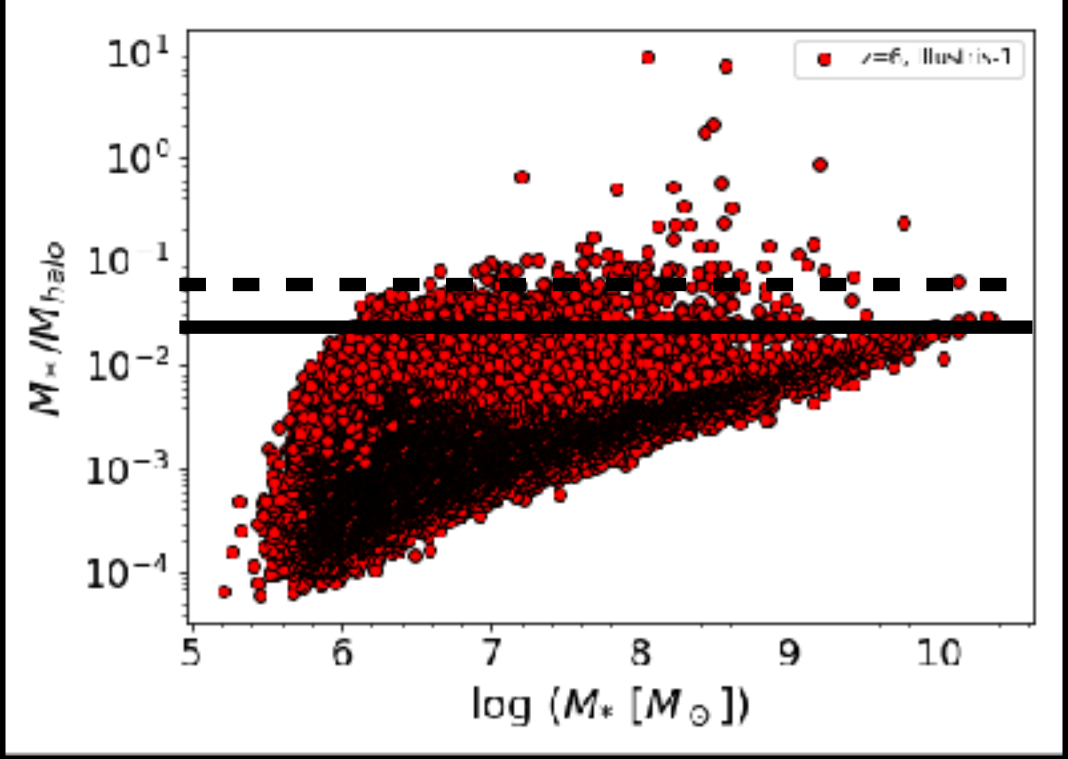
For some combinations (w_0, w_a) the slower growth factor make it impossible to grow large galaxies at the observed redshift

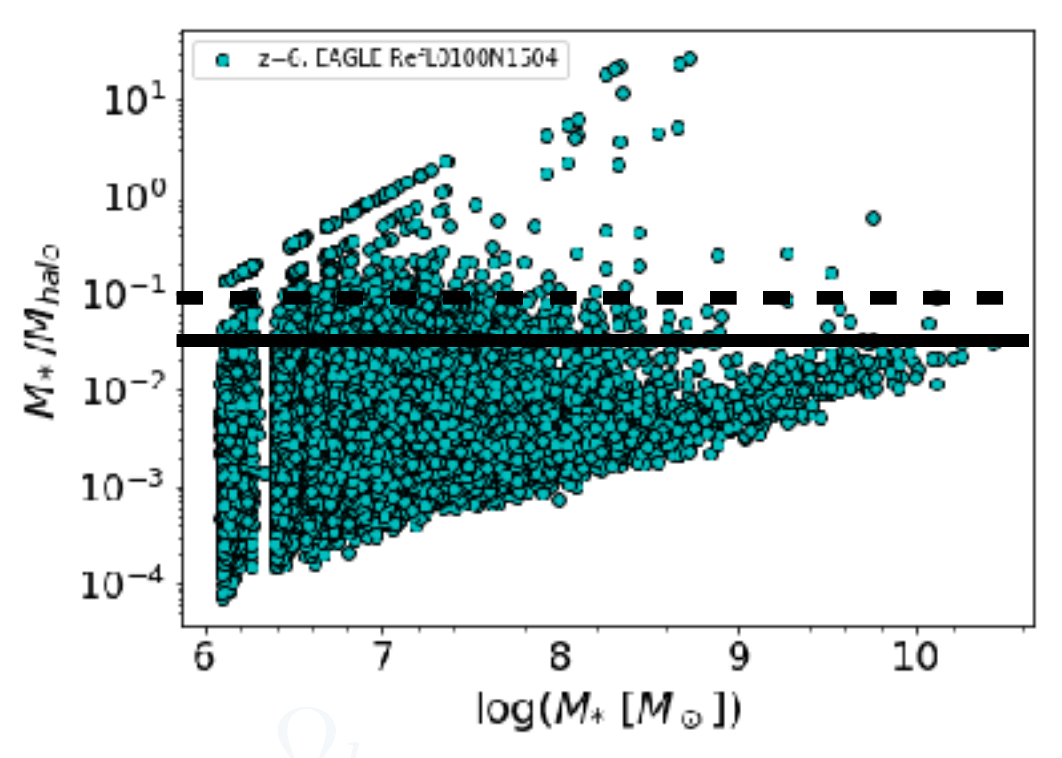
I. The Stellar Mass Function of optical/UV galaxies at z=6

To be CONSERVATIVE we consider the maximum M*/M ratio at the considered redshift

$$\frac{M_*}{M} \leq \frac{\Omega_b}{\Omega} F$$

If all baryons are in stars	F=1
LCDM simulations suggest when the most massive halos are considered	F< 0.5
Best fit value	F=0.3





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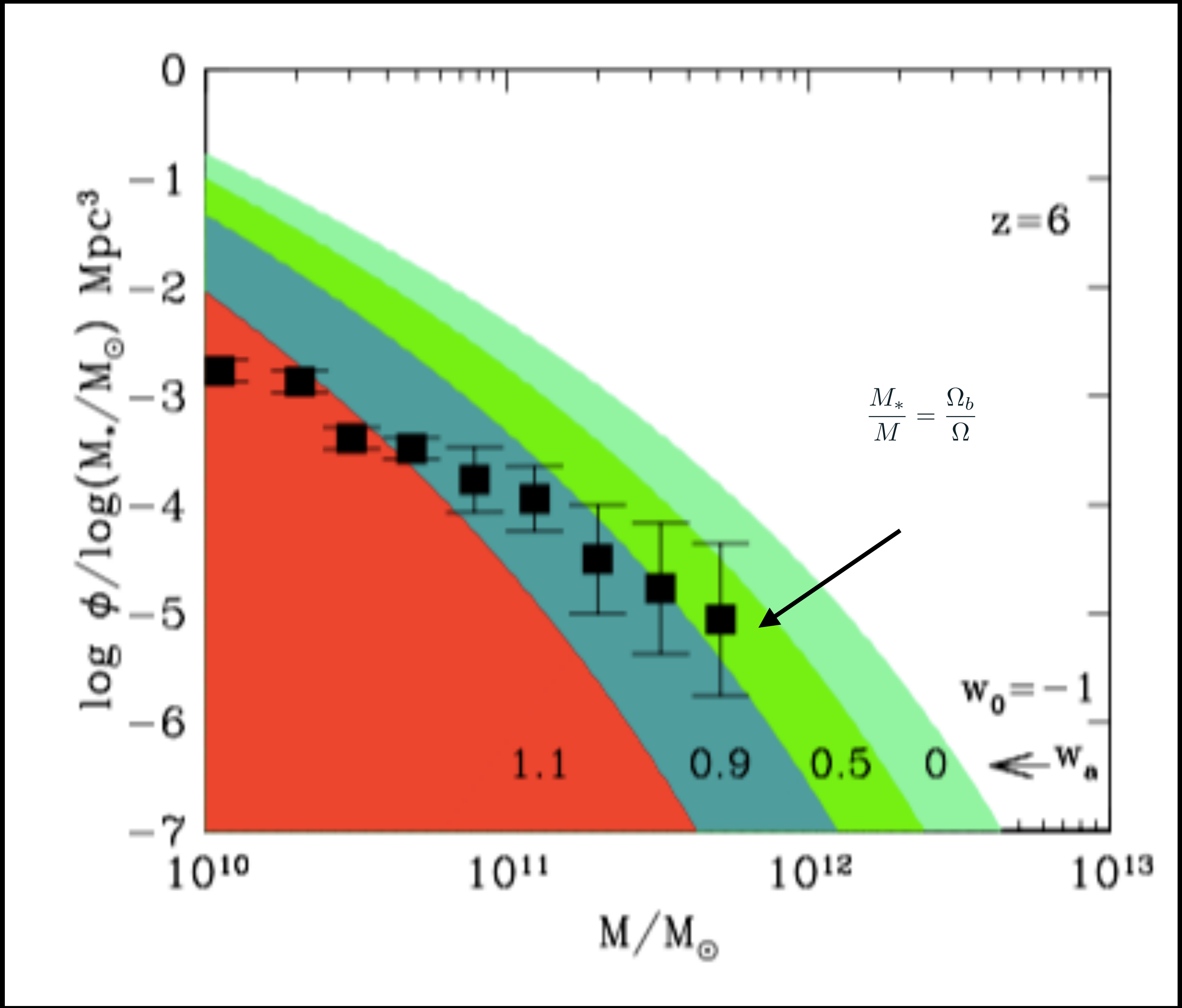
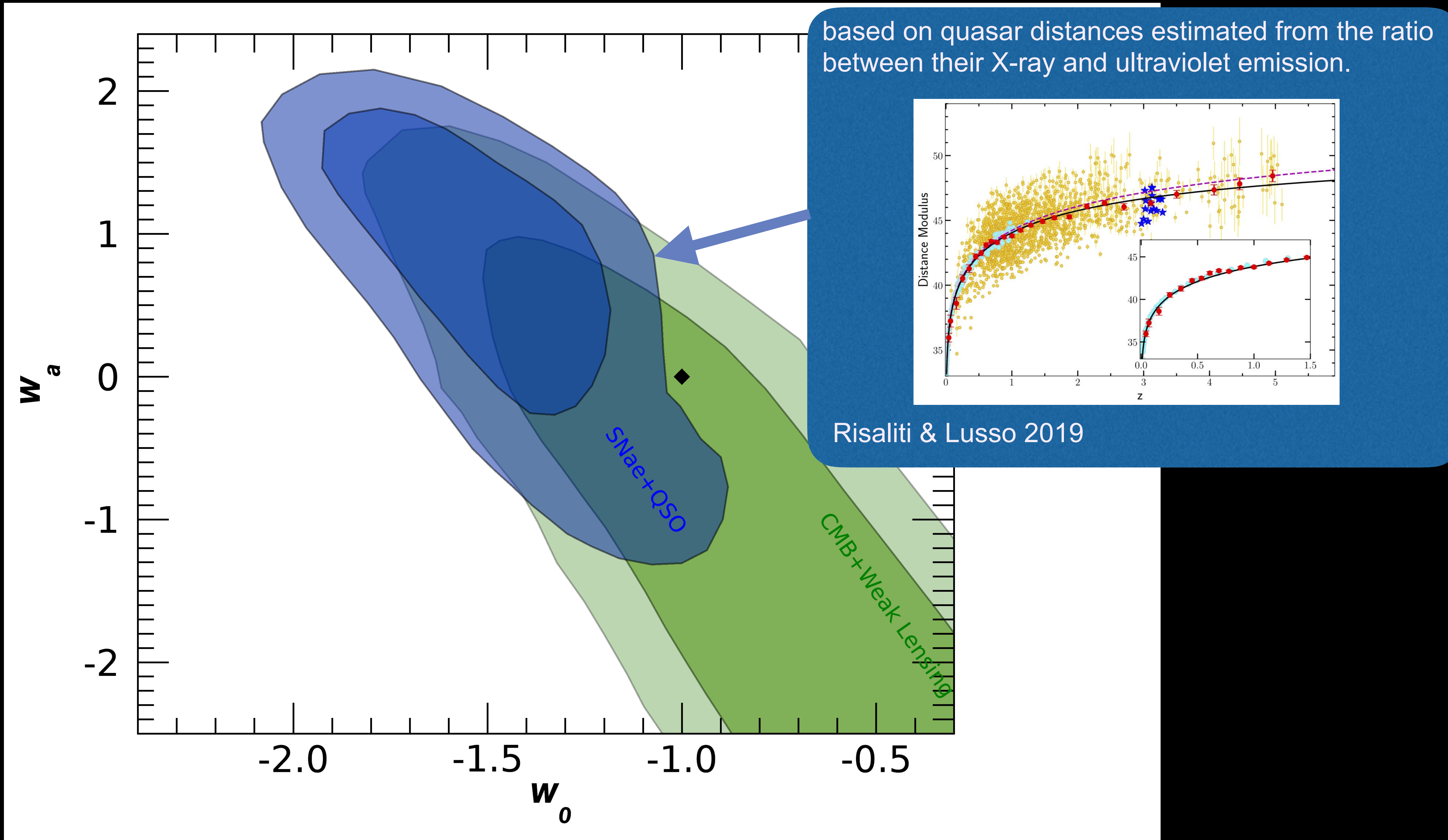


The largest the measured stellar masses
The stronger are the constraints

If M* are obtained from SED fitting assuming
Kennicut IMF constitutes the most conservative approach

Robust with respect to

- star formation process
- values of H_0
- Baryon physics



For each combination (w_0, w_a)

– compute the maximum abundance of galaxies with observed M* at z=6 and z=7.

– compute the probability of observing such an abundance (perturbing observed LF through a Monte Carlo simulation including statistical and systematic errors)

Derive exclusion probabilities of different cosmological model from CANDELS data

We first consider two CANDELS field as in Grazian et al. 2014

Stellar masses derived from SED fitting

For each galaxy we run a Monte Carlo simulation. For each object we consider the effect of

- Changing the adopted star formation law
  - exponential $SFH \propto \exp(-t/\tau)$
  - inverted expon. $SFH \propto \exp(+t/\tau)$
  - delayed $SFH \propto (t^2/\tau)\exp(+t/\tau)$
- Photometric redshifts
- Cosmic variance
- Extinction ($0 < E(B-V) < 1.1$) and extinction curves (Calzetti, SMC, LMC)
- Metallicity $Z = 0.02\ Z_\odot$ to $Z = 2.5\ Z_\odot$

To be conservative, we adopt a Kennicut IMF (other considered IMF yield larger stellar masses)

For each stellar mass bin, we derive the different $\Phi(M^*, z=6)$ obtained when the above quantities are a allowed to vary

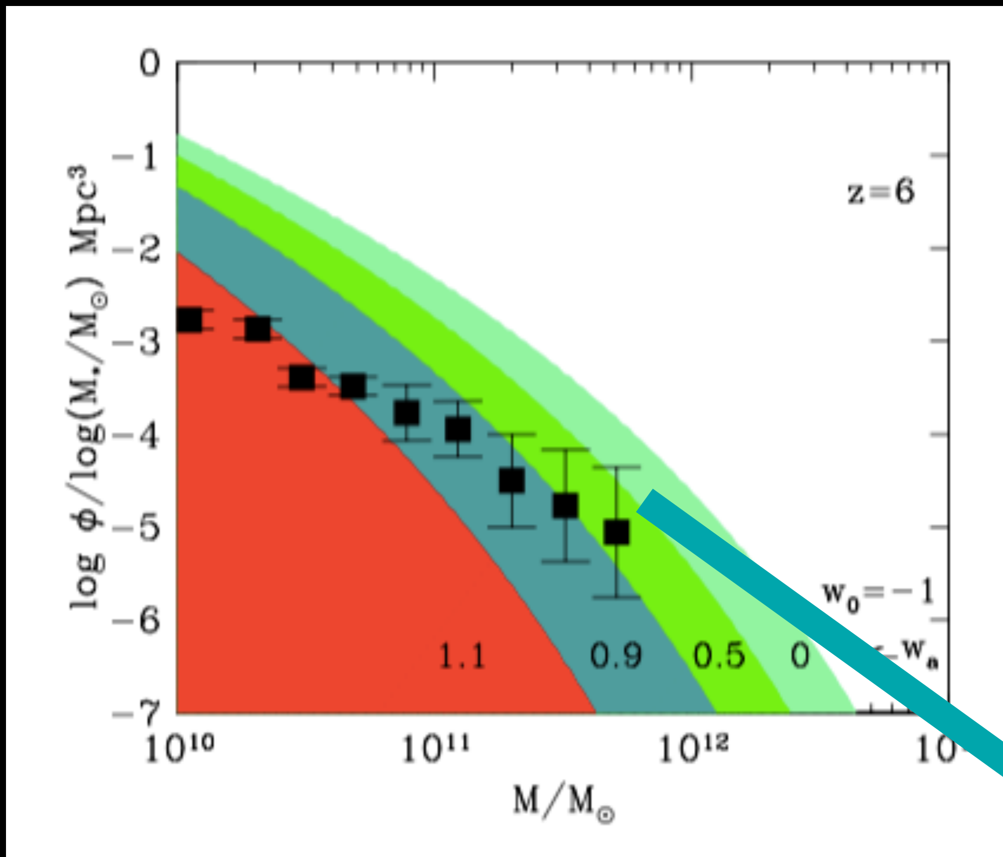
➜ For each M* we derive the whole distribution of measured Φ associated random and systematic uncertainties

Choose a cosmological model (w_0, w_a)

rescale the observed values of Φ to the chosen cosmology

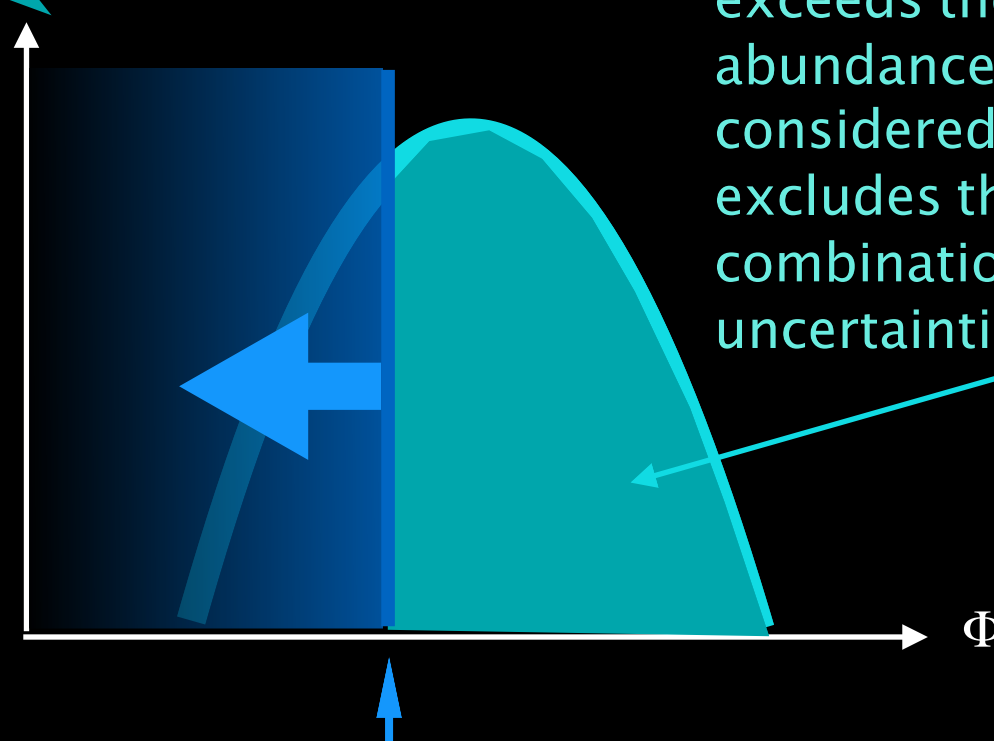
For each cosmological model, we compute the probability that the above uncertainties result in a measured $\Phi(M^*, z=6)$ exceeding the abundance of DM halos

I. The Stellar Mass Function of optical/UV galaxies at z=6



Computing the exclusion probability for each (w_0,w_a) combination

Distribution of observed values Φ at a given M* in a given cosmology (w_0,w_a)



Probability that measured Φ exceeds the maximum abundance of halos in the considered cosmology (i.e. it excludes the considered combination w_0,w_a) when all uncertainties are considered

Maximum abundance of halos corresponding to M*

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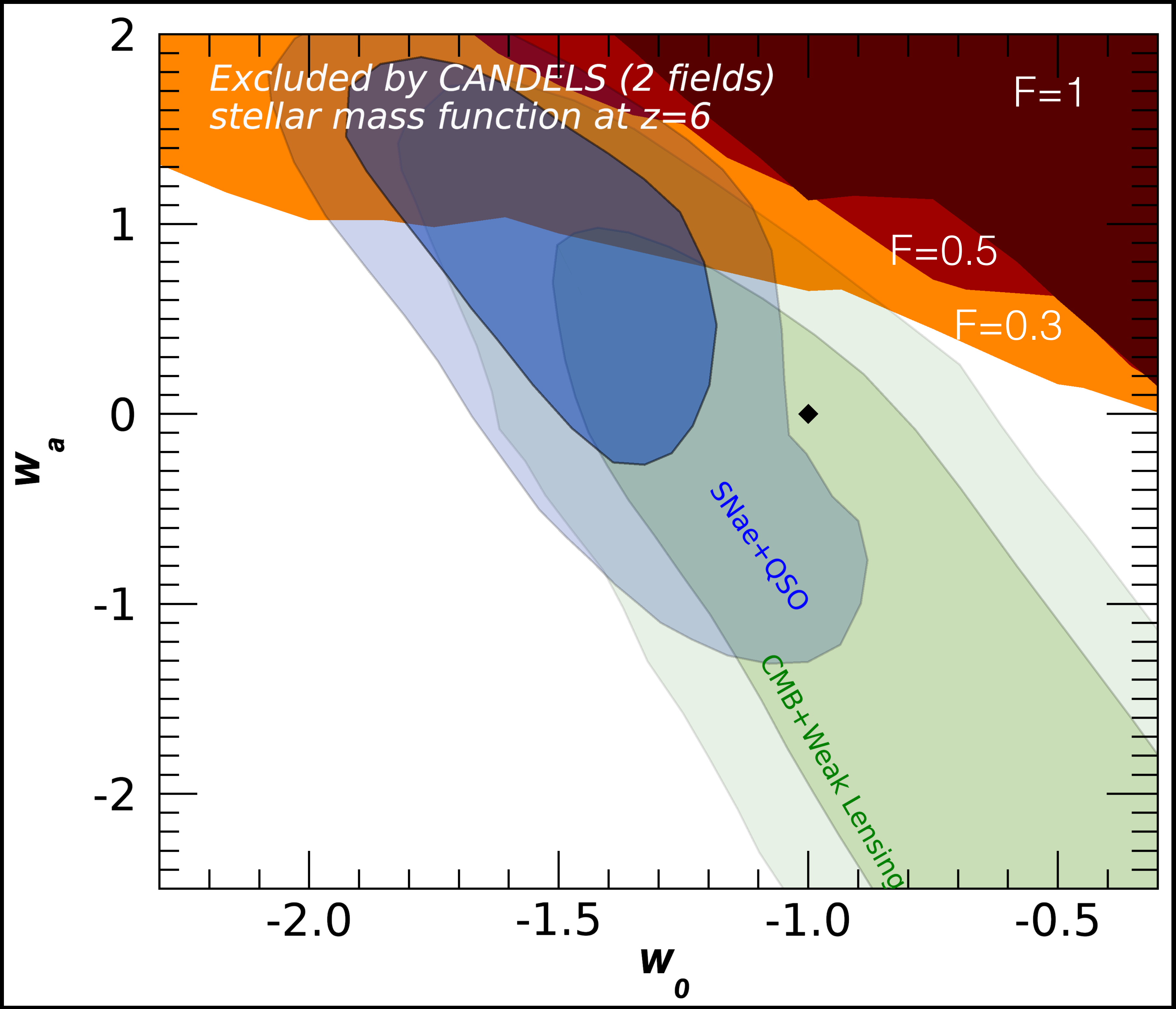

2-σ exclusion

Using LF from Grazian et al. 2015 (two CANDELS fields)

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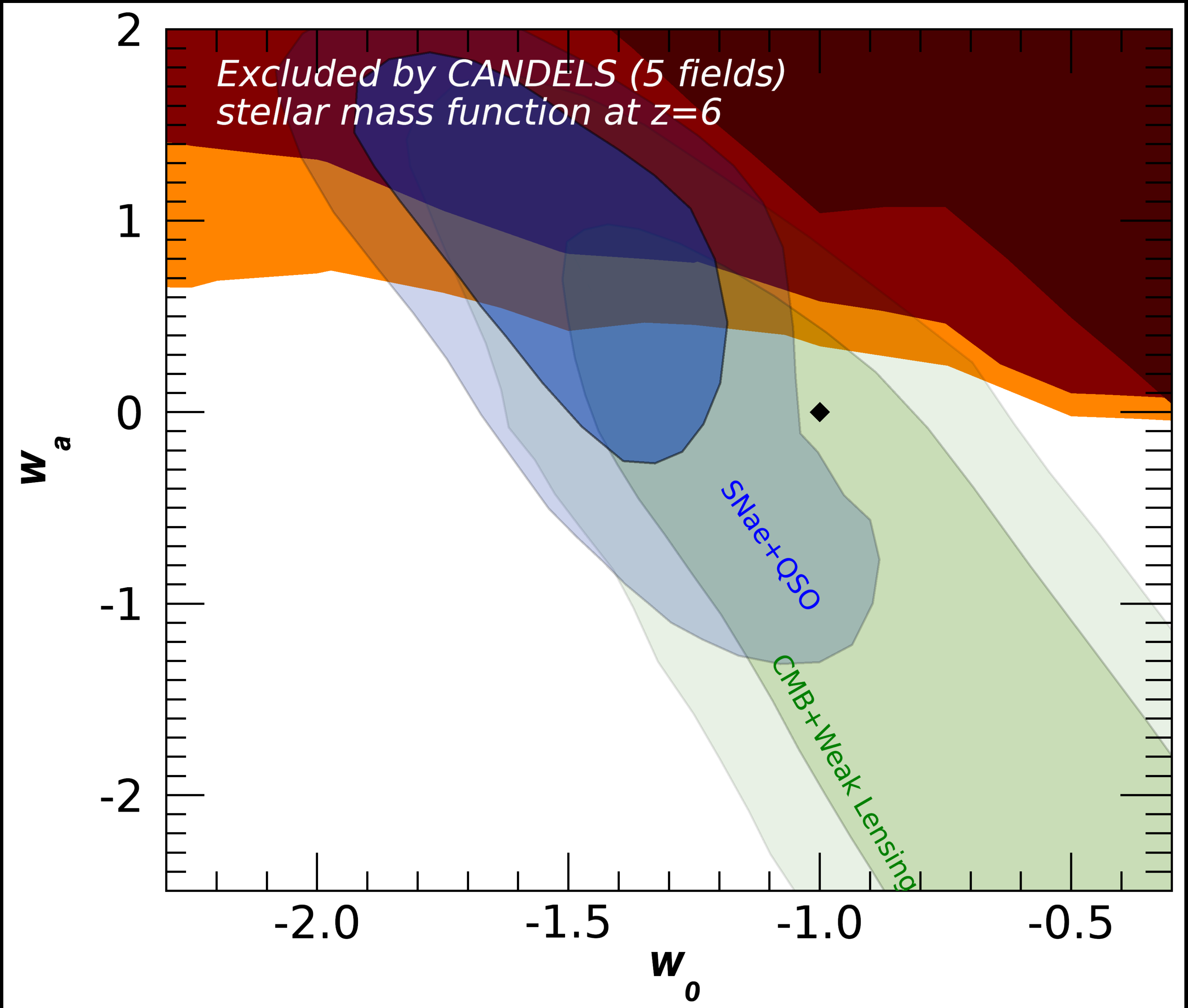


Simulating the statistical effect of doubling the number of galaxies used to derive the LF

II. The Number density of sub galaxies at z=4.5-5.5

Galaxies identified in rest-frame optical and UV are known to under-represent the most massive galaxies,

Massive, star-forming, dusty galaxies are however detectable at sub-millimetre wavelengths

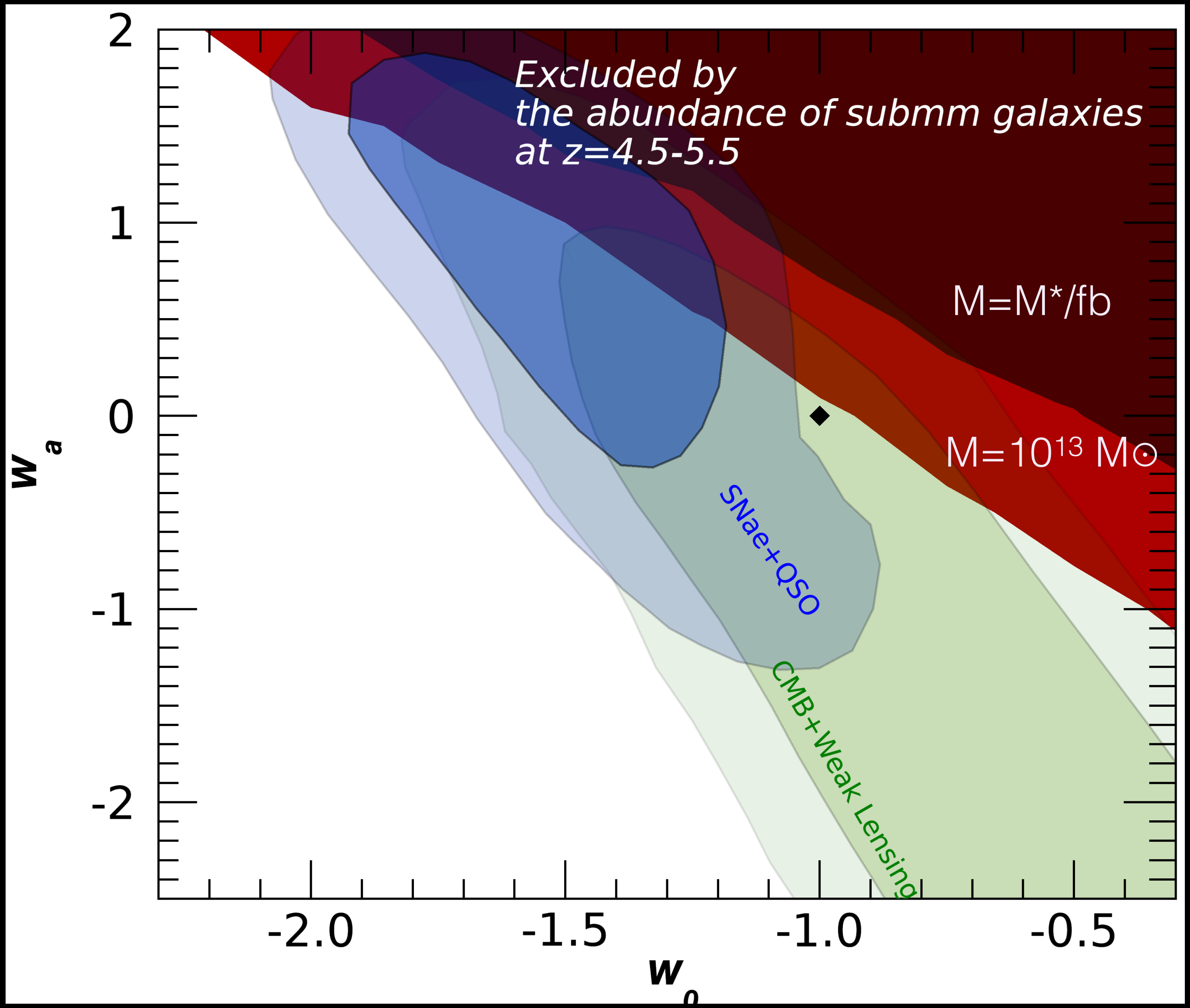
ALMA observations at sub-millimetre (870 μm) wavelengths by Wang et al. (2019) lead to the discovery of 39 galaxies star-forming objects at z > 3, which are unseen in even the deepest near-infrared (H- band) imaging with the Hubble Space Telescope (H-dropouts),

These are massive galaxies with median stellar mass extending up to $M_* \approx 3 \cdot 10^{11}$ M⊙, with median mass $M_* \approx 4 \cdot 10^{10}$ M⊙.

In this case, an estimate of the corresponding DM halo mass can be derived from the clustering

- Measured cross correlation amplitude A(ϑ)
- Correlation length r_0 (Limber equation)
- Galaxy bias b
- Variance of the DM field

→ DM mass $M > 10^{13}$ M⊙



III. Rareness of SPT031158 at z = 6.9

The most massive system detected at $z \geq 6$ identified in the 2500 deg^2 South Pole Telescope (SPT) survey (Marrone et al. 2018).

SFR ≈ 2900 $M_\odot$/yr, an estimated magnification μ = 2

Huge mass content $M_{H_2} \approx 3.1 \cdot 10^{11} M_\odot$.

Assuming $f_{H_2} = M_{H_2}/(M_* + M_{H_2}) = 0.4 - 0.8$. Even assuming $M = M_b/f_b$

DM mass $M = 2 - 6 \cdot 10^{12} M_\odot$

we compute the Poisson probability of finding such a massive object within the volume probed by the SPT survey,

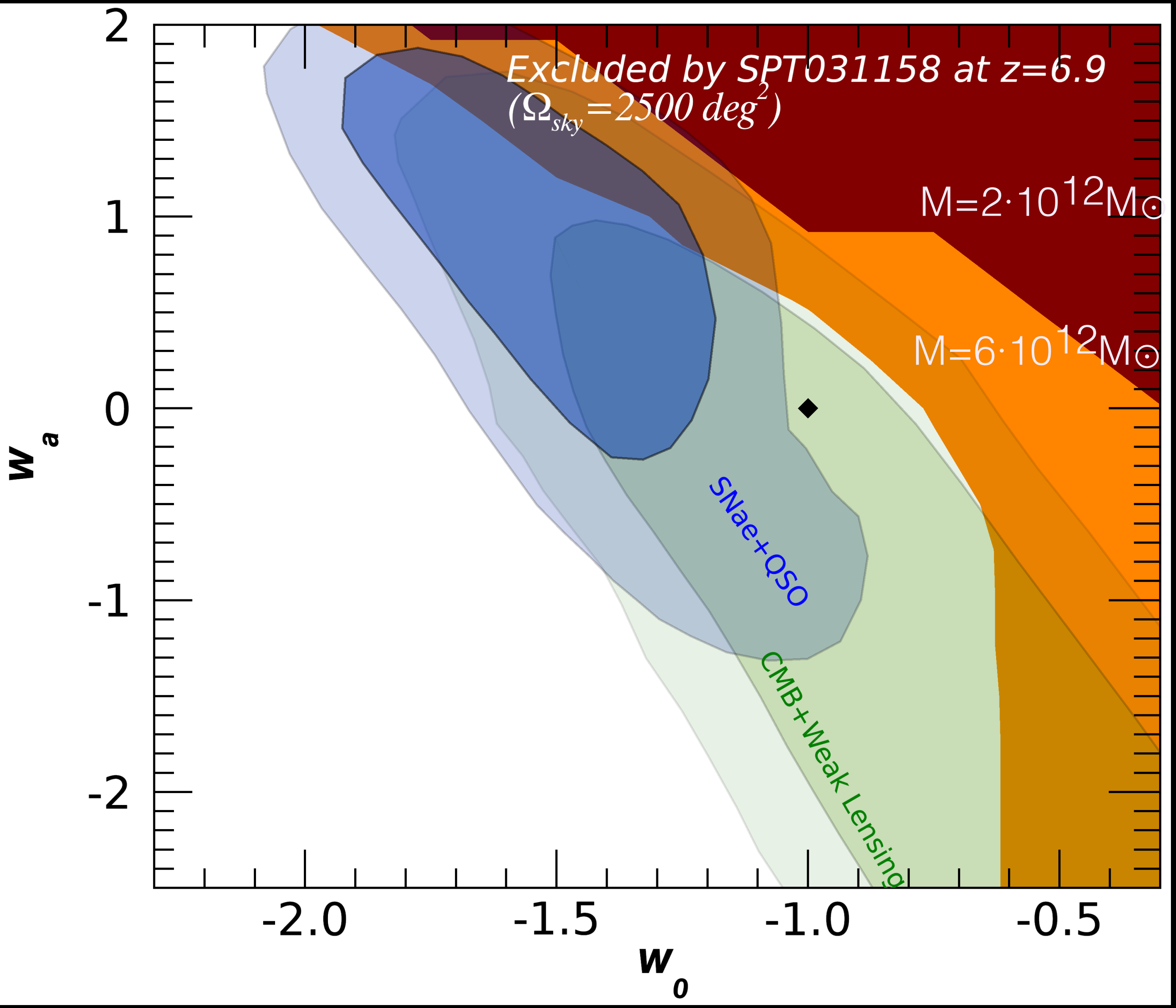
For the different DDE models (w_0, w_a).

- Compute N(M, z) number of systems with mass M and higher at redshift z and higher expected in the sky area $f_{sky} = 2500\ deg^2$ covered by the SPT survey
- Compute such a number for the obs. values (i.e., z=6.9, and $M = 2{-}6 \cdot 10^{12} M_\odot$) obtaining N_{obj}
- Compute N_{rare} defined as N(M, z) only for the masses M and redshifts z for which $N(M, z) \geq N_{obj}$

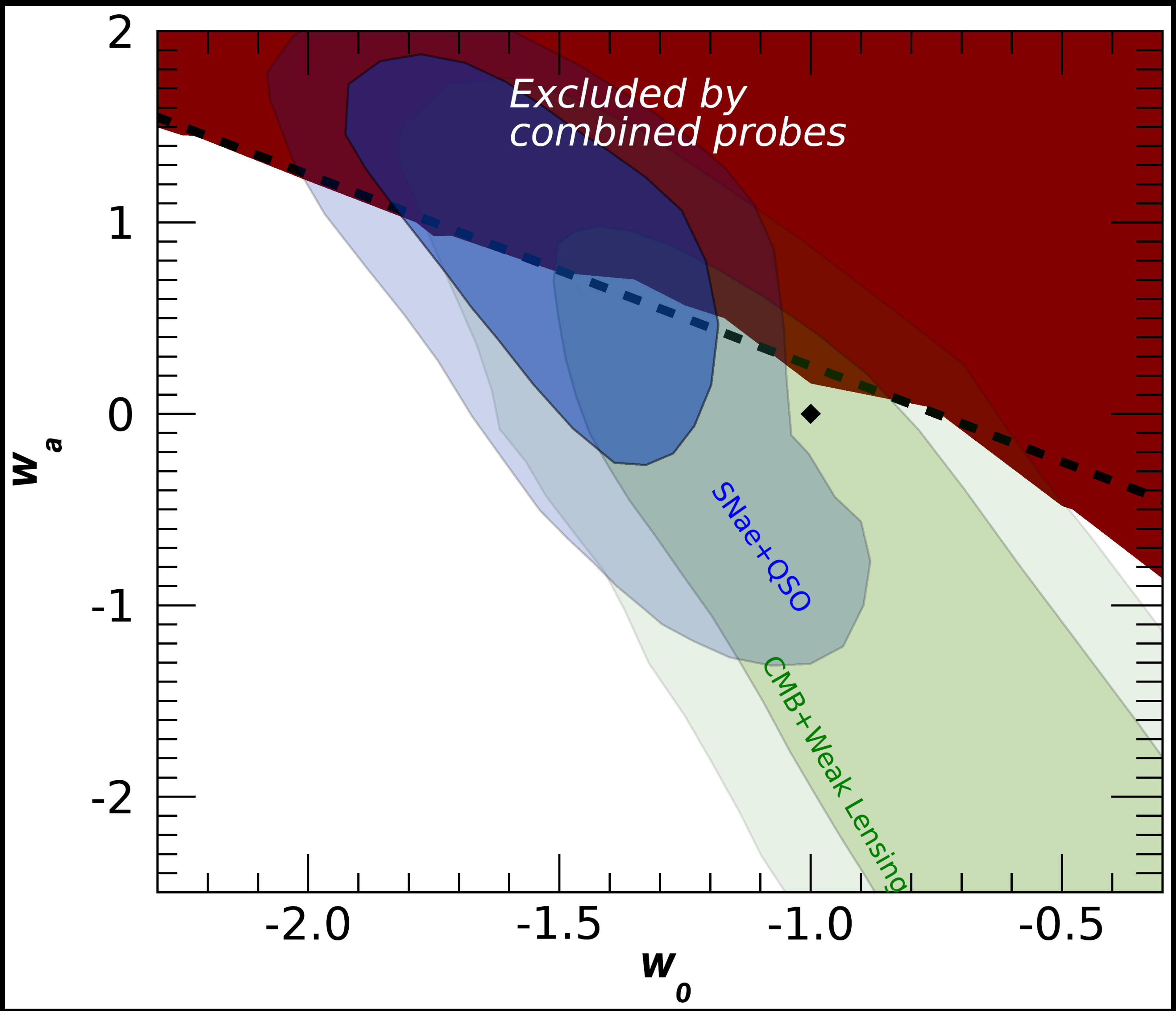
Method by Harrison & Hotchkiss 2013

The Poisson probability of observing at least one system with both greater mass and redshift than the one which has been observed is

$R_{>M,>z} = 1 - \exp(-N_{rare})$



Combining the above probes under the most conservative assumptions



Competitive with existing probes

Positive evolution of w disfavoured

A major fraction of the region favoured by AGN is ruled out

Results consistent with cosmological constant

Exclude models with

$$w_a \geq -3/4 - (w_0 + 3/2)$$

Al*most entirely rule out* the quintessence models where initially $w > -1$ and w decreases as the scalar rolls down the potential (cooling models), which occupy most of the region $w_0 > -1$, $w_a > 0$ (see Barger, Guarnaccia, Marfatia 2005).

These typically arise in models of dynamical supersymmtery breaking (Binetruy 1999; Masiero, Pietroni, Rosati 2000) and supergravity (Brax and Martin 1999; Copeland, Nunes, Rosati 2000) including the freezing models in Caldwell & Linder (2005) in which the potential has a minimum at $\varphi = \infty$.

For phantom models with $w_0 < -1$ (see Caldwell 2002), our constraint $w_a \geq -3/4-(w_0+3/2)$ excludes a major portion of the parameter space corresponding to models for which the equation of state crossed the phantom divide line $w = -1$ from a higher value.

CONCLUSIONS

Our results exclude DDE with an equation of state rapidly evolving with z   dw/da

Competitive and complementary with existing probes

This limit has an impact on a wide class of models with a 'freezing' behaviour ($\ddot{\varphi} < 0$) of the DE scalar field (see Caldwell & Linder 2005; Linder 2006).

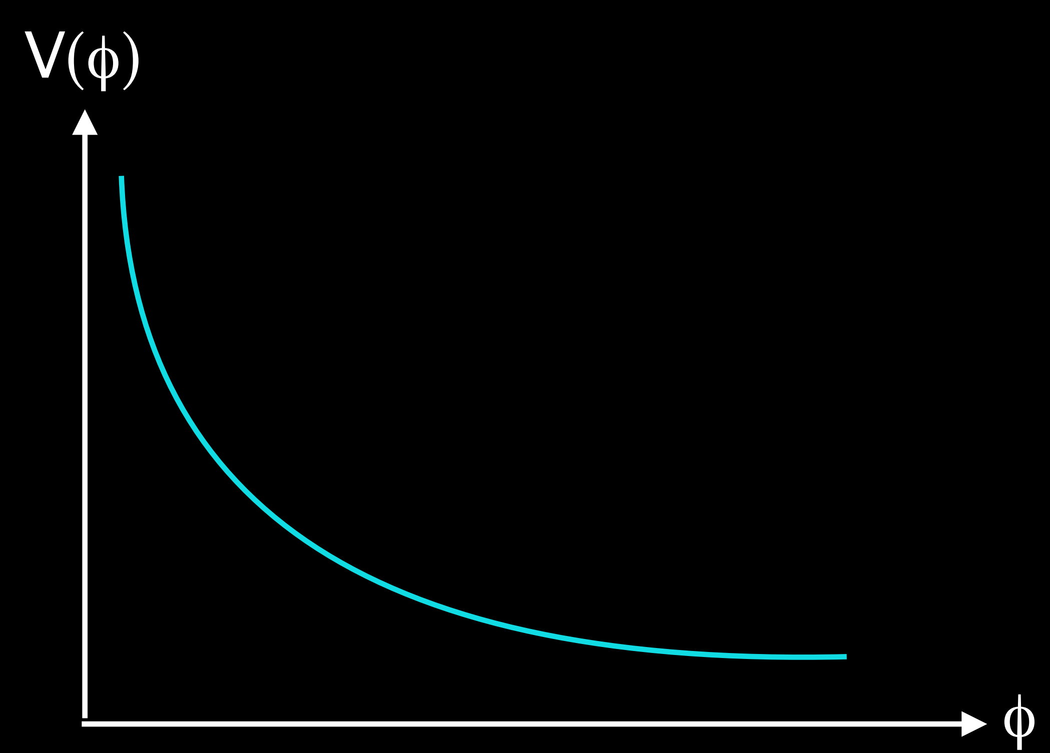
$$\ddot{\varphi} = -V_{,\varphi} - 3H\dot{\varphi}$$

Two regimes:

'thawing' solutions with $\ddot{\phi} > 0$ and

'freezing' solutions with $\ddot{\phi} < 0$

The two regimes are separated by $dw_a/da = 3(1 - w^2)/a$ (Linder 2006)



Supergravity (SUGRA) inspired models (Brax & Martin 1999) - well fitted by $w_0 \approx -0.82$ and $w_a \approx 0.58$ (Linder 2003) - are strongly disfavoured